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In-process fast surface measurement using wavelength scanning interferometry

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Abstract. A wavelength scanning interferometry system for fast areal surface measurement of micro and nano-scale surfaces which is immune to environmental noise is introduced in this paper. It can be used for surface measurement of discontinuous surface profiles by producing phase shifts without any mechanical scanning process. White light spectral scanning interferometry, together with an acousto-optic tuneable filtering technique, is used to measure both smooth surfaces and those with large step heights. An active servo control system is used to serve as a phase compensating mechanism to eliminate the effects of environmental noise. The system can be used for on-line or in-process measurement on a shop floor.

Introduction

Structured surfaces are a fundamental building block for a wide range of applications [1]. Many of these examples are beyond the state-of-the-art for surface-measurement science, in terms of surface topographical characteristics such as extremity of size, ultra-high precision, complexity of shape, or combinations of these aspects. The ability to perform quantitative measurements and characterisation on such surfaces under the required assessment conditions and at high measurement speed is very limited. This technology gap will seriously hamper a wide range of cutting edge technologies [2].

A fundamentally improved measurement technology for structured surface measurement, based on the wavelength scanning interferometry method [3] and general purpose graphics processing unit (GPGPU) technique is presented in this paper. The technology attempts to create a new kind of measurement system to replace electro-mechanical scanning with white-light interferometry, and develop a compact system that is fast, robust, immune to environmental turbulence and suitable for on-line/in-process surface measurement in a CNC machine centre or production line. Surface topography is calculated in real time through analysing the interferograms using a GPGPU. This innovative measurement technique delivers the whole measurement cycle in less than 2 seconds with a measurement range of up to a few hundred micrometers with nanometre accuracy.

Measurement principle

The measurement principle is based on measuring the phase shift of a reflected optical signal using wavelength scanning techniques by using an acousto-optic tuneable filter (AOTF). The configuration of the wavelength scanning surface measurement system is illustrated in Fig. 1(a). The measurement system is composed of two interferometers that share a common optical path. The measurement interferometer illuminated by a white light source is used to acquire the three dimensional surface profile of the sample in real time. The reference interferometer illuminated by a superluminescent light emitting diode (SLED) is used to monitor and compensate for the environmental noise. As the two interferometers suffer similar environmental noise, the measurement interferometer will be capable of measuring surface information once the reference interferometer is “locked” into compensation mode. The system adopts a Linnik configuration in which the light beam is split by the Beamsplitter. Light reflected by the sample and the reference mirror are combined by the Beamsplitter to generate an interferogram. A Dichroic beamsplitter 2 is

used to separate the measured interferogram signal and the reference signal. The interferograms are detected by a high speed CCD camera. The selected light wavelength of an AOTF is determined by:

$$\lambda = \Delta n \alpha \frac{v_a}{f_a} \quad (1)$$

where Δn is the birefringence of the crystal used as the diffraction material, α is a complex parameter depending on the design of the AOTF, and v_a and f_a are the velocity and frequency of the acoustic wave respectively. The wavelength of the light that is selected by this diffraction can therefore be varied simply by changing the driving frequency f_a . As a result, different wavelengths of light will pass through the AOTF in sequence so that a series of interferograms of different wavelengths will be detected by the CCD.

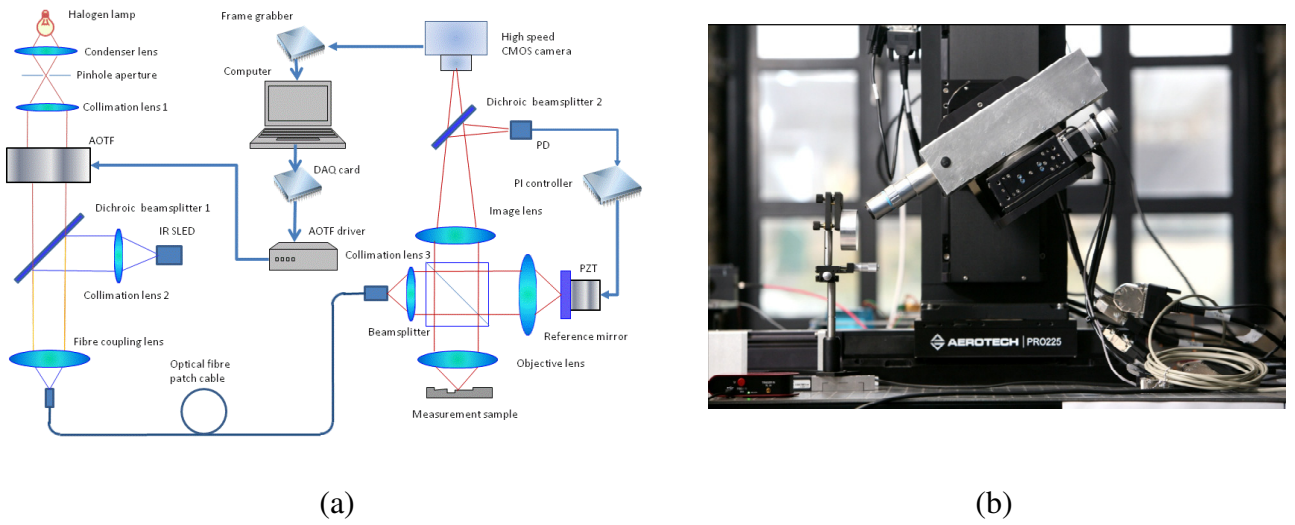


Figure 1. Schematic diagram of the wavelength scanning interferometry system

Intensities detected by pixel (x, y) of the CCD camera that correspond to one point on the test surface, can be expressed by

$$I(x, y; k) = a(x, y; k) + b(x, y; k) \cos(2\pi k h(x, y)) \quad (2)$$

The optical path different $h(x, y)$ is given by

$$h(x, y) = \frac{\Delta \phi(x, y, \Delta k)}{2\pi \Delta k} \quad (3)$$

Since the change of k can be calibrated first by using an optical spectral analyzer, the main issue here is how to calculate the phase change. There are many phase calculation methods that may be employed in spectral scanning interferometry [7-10]. In this paper, we use phase calculation by Fourier transform because it is fast, accurate and insensitive to intensity noise. By applying the proper algorithm for the phase distribution of each CCD pixel, the height map of the surface to be measured can be acquired.

Experimental setup

The prototype of the current measurement system is shown in Fig. 1(b). The interferometer is mounted on a 4 axis stage, which gives the system 4 freedoms to make it easy to locate and focus the interferometry system onto the sample surface. It is especially practical when applying the system to a CNC system such as a diamond turning machine.

Surface measurement in the workshop/manufacturing environment has been difficult to achieve using interferometric methods because they are so sensitive to vibrations and air turbulence [4]. Our system will monitor the noise during measurement. A compensating piezoelectric translator (PZT) attached to the reference mirror is driven by servo electronics and is used to compensate for any environmentally induced noise. The reference interferometer will be locked at around quadrature to maximize sensitivity to environmental disturbance. Most normal floor vibration occurs in the range of 20 to 200 Hz [4]. Modern PZTs have a resolution up to 0.05 nm and a frequency response of 35 kHz (e.g. P-249.10, PI Company); the noise compensation can be very quick and accurate provided that the load is light. This technique has been effectively tested and proved in our previous research [5-6].

The experimental system uses a high speed CCD camera which captures 300 frames during the wavelength scanning process; each pixel of the CCD camera collects 300 intensity values. The intensity values of just one pixel can be processed at a time to obtain the information of one point of the sample surface if a single core CPU is used. So the computing structure required to be repeated 337334 times in a sequential execution manner to analyse the structure of a surface captured by (672x502) pixels of the CCD camera. A graphics processing unit (GPU) GeForce GTX 280 with 240 cores has been used to accelerate the computing process. The massive parallel programming capability of the GPGPU has accelerated the floating point calculation throughput 10 times more than multicore CPUs.

Measurement and results

The method described in the previous section was used to measure two standard height specimens. In the experiment, the radio frequency applied to the AOTF (Model LSGDN-1, SIPAT Co.) was scanned from 80MHz to 110MHz in steps of 10 kHz, corresponding to a wavelength interval of 0.48nm. This range of radio frequency provides a range of scanning wavelength from 680.8nm to 529.4nm. During the wavelength scanning process, 300 interferograms were recorded by the high speed CCD camera (Model OK-AM1131, JoinHope Image Tech. Ltd.) at a frame rate of 100 frames/s. Figure 4(a) shows a CCD captured frame of a 2.970 μ m step height standard as supplied by the National Physical Laboratory (NPL), UK.

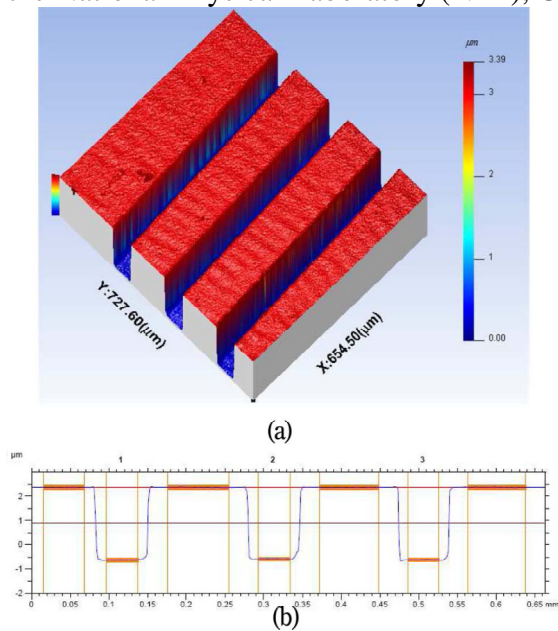


Figure 4. Measurement results of a 2.97 μ m standard step: (a) The measured surface (b) A cross-section profile

This sample has been processed according to the above proposed measurement procedure and an areal surface view has been obtained as shown in figure 4(a). Clearly there are three grooves in the sample surface. Figure 4(b) shows the section view of the grooves. The measured average step height is 2.971 μ m. The measurement error is 1nm.

The effectiveness of the vibration compensation was investigated by carrying out the following experiments. Firstly, a semiconductor daughterboard sample was measured without inducing mechanical disturbance. The surface step height measured $4.7564\text{ }\mu\text{m}$. Next, a 40 Hz and 400 nm peak-to-peak sinusoidal mechanical disturbance using a PZT was applied to the reference mirror. During the disturbance, the same surface step height measured was $11.711\text{ }\mu\text{m}$. However, the surface roughness signal is completely distorted. When the vibration compensation is switched on, a reduction in the disturbance movement of the fringe pattern is clearly observed. The measurement of the sample at this stage is carried out. The data were retrieved as the original measurement and illustrates that the compensation vibration can be used to overcome environmental disturbance. The measured step height is $4.7429\text{ }\mu\text{m}$. The measured images and a section of the measured profiles are shown in figure 7. The difference between the two measured step height values is 13.5 nm, in comparison to the two measured results. The observed disturbance attenuation between the second and the third parts of the experiment was 12.2 dB according to the reference interferometer signal output, which is in agreement with the measured sample error.

Discussion

We have proposed a surface measurement technique with active control of environmental noise that utilizes wavelength scanning interferometry. Nanometre accuracy surface measurement results have been carried for micrometre step height samples. Disturbance has been reduced to 12.2dB at 40Hz vibration frequency. The measurement speed is only restricted by the frame rate of the CCD camera and the data processing speed.

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